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14. Abstract

The main purpose of this project is to investigate the feasibility and efficacy of using a stereo display workstation for lung cancer screening on CT images. The tasks included in this project are development and evaluation of stereo image projection and display for chest CT images, observer performance evaluation for the stereo display, and stereo feature analysis and comparison to the conventionally used display methods for lung cancer detection. In the previous report periods, we have built a stereo display workstation for chest CT images, then conducted and analyzed a pilot observer performance study. In this annual report period, we have conducted a main observer performance study as scheduled in the proposal, and investigated spectrophotometric characteristics for further understanding and improving stereo display. The tasks we did in this period are: 1. Conducting a main study: the main study was organized as a retrospective study of 100 lung cancer screening cases containing about 560 nodules. The cases were interpreted in each of the 3 display modes by 8 radiologists who have extensive experience in reading chest CT. Collection of the interpretation data has been completed for analysis. About 1159 suspicious lesions, including true and false positives have been found in the readings and will be used for evaluation of the 3 tested display modes. 2. Investigating spectrophotometric characteristics of stereographic image pairs: to further understand the characteristics of stereo imaging and displaying, we analyzed differences in spectrophotometric characteristics between images acquired during stereographic imaging. We found that though uniform global differences can easily be corrected by applying traditional histogram matching techniques, these methods are not capable of dealing with differences that are object or distance dependent. We have developed a procedure to adjust, locally, visual characteristics of one image in a stereo pair to match the alternate image. The fully automatic procedure is able to remove visible differences in most cases, therefore enhance the quality of stereo 3D visualization.

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INTRODUCTION

Lung cancer is a leading cause of death in the United States [1,2]. The results from several large lung cancer screening studies indicate that early detection and treatment can reduce mortality rate in most types of lung cancer cases [3-6]. Currently, low-dose CT scanner is a primary tool used for lung cancer screening. For each screening case, a set of image slices covering entire lung area is generated and viewed on display workstations. Despite of 3D format of CT datasets, the conventional reading method for lung CT image interpretation is to read images slice-by-slice. This reading method requires radiologists to mentally reconstruct images in 3D space from a set of 2D images to differentiate normal tubular structures from nodules. Furthermore, with improved technology for CT scanner, higher resolution imaging techniques produce more images per scan, which eventually will exceed radiologists' ability to read cases in slice-by-slice mode. The need of 3D data presentation of CT images has become crucial for ever-increasing numbers of images generated from CT scanner and for improvement of radiologists' performance on image data interpretation. We have proposed to develop a stereo display workstation for reading lung CT images. Stereopsis is the mechanism used in human vision system to perceive objects in real world. The 3D display using stereoscopic projection should produce a natural and efficient solution for 3D data presentation. In this proposal, we hypothesized that the efficacy of lung cancer screening using CT scanned images can be increased by use of a suitable designed stereoscopic display. Specifically, we expect that both efficiency, and accuracy for the detection of lung nodules, will be increased significantly over what can be achieved when reading cases in currently used display modes. To achieve the goals in this proposal, we have specified our aims as followings:

1) Develop and integrate the hardware and software required to implement a stereoscopic display tailored to chest CT images.
2) Use a subset of lung cancer cases, verified either by pathology or by followup, to evaluate the display system.
3) Perform a retrospective study to measure relative accuracy and reading efficiency, for detection and classification of lung nodules, between three display modes including stereoscopic 3D mode from this project, and other two commonly used modes, slice-by-slice and maximum-intensity-projection (MIP) thick slice.

BODY

Perform Main Study (Task 11)

We have conducted the main observer performance study that uses larger database and improved study design based on the feedbacks from the pilot study. The main study was organized as a retrospective study of about 560 nodules in 100 cases. Eight radiologists who have extensive experience in reading chest CT, have participated the study. Among the 8 radiologists, 4 of them were in the pilot study. Those who have not been in the pilot study had a short training course on the study procedures before the actual study. The data collecting has been completed. A total of 1159 suspicious lesions, including true and false findings, have been found during the readings from all readers in the 3 display modes. The initial findings from all readers and all display modes were first pooled together for consolidating and establishing consensus truth. Same lesions found in multiple display modes were identified by comparing and matching 3-dimensional locations.

We are now in the process of analyzing the data for the performance of lung nodule detection with the 3 display modes.

Investigating Spectrophotometric Characteristics of Stereographic Image Pairs

To further understand stereo image features and stereo display characteristics, we investigated spectrophotometric characterstics of stereographics of stereographic image pairs. Differences in spectrophotometric characteristics between images acquired during stereographic imaging may significantly reduce the effectiveness of their subsequent display or analysis. While uniform global differences can easily be corrected by applying traditional histogram matching techniques, these methods are not capable of dealing with differences that are object or distance dependent. We have developed a procedure to adjust locally, visual characteristics of one image in a stereo pair to match the alternate image. Objects, and their boundaries, are segmented in both images. Non-uniform regions and very small objects are either suppressed or combined into a single large region, while larger objects are retained. Local pattern matching, by varying the horizontal displacement between images, allows a correspondence to be established between boundaries of the objects on the two images, and hence a correspondence between connected components. For each pair of corresponding connected components, a linear correction function that minimizes the sum-of-squares difference is determined. Each pixel in the image to be corrected is adjusted by interpolating between all of the correction functions based on the distance of the pixel from each of the centers-of-mass of the individual connected regions. The fully automatic procedure is able to remove visible differences in most cases.

KEY RESEARCH ACCOMPLISHMENTS:

- Completed a main study, and collected and organized the data from the study.
- Studied spectrophotometric characteristics of stereographic image pairs for better understanding stereo image quality and display issues.

REPORTABLE OUTCOMES

Peer reviewed paper

Real-Time Stereographic Rendering and Display of Medical Images With Programmable GPUs. Computerized Medical Imaging and Graphics, 2007 in press.

Characterization of Radiologists' Search Strategies for Lung Nodule Detection: Slice-Based Versus Volumetric Displays. Journal of Digital Imaging, 2007 in press.

Presentation & Proceedings

Spectrophotometric Correction of Stereeographic Image Pairs. 2008 Society of Imaging Science and Technology Annual Meeting. January 10 – 12, 2008, China.

Grant application

Immersive Environment for High-Quality, Portable Display of 3-D Radiographic Datasets. Submitted to NIH, September 2007.

CONCLUSION

Our primary objective is to determine whether a stereoscopic display concept has potential for improving the efficiency and accuracy of chest CT interpretation for lung cancer screening. In this report period, our main tasks were to conduct a main study extended from the pilot study, and to further explore characteristics of stereo image, related to either quality or both quality and display.

During this report period, we have finished the main observer study and data collected from the study. The findings from 8 readers and 3 display modes were pooled together for further analysis. All findings, including true and false lesions were verified and matched when the same lesions were found in multiple display modes, based on their 3-dinmasional locations. The consolidated data will be used for consensus truth of lung nodule and performance evaluation of the 3 display modes, which are our ongoing research for this project.

Further studies on stereo image characteristics indicate the importance of stereophotometric consistency between two stereo images for stereo image quality and display. Automatic detection and correction difference of stereophotometric characteristics between two stereo images is achievable using the method we developed and can be efficiently used for improving display quality of stereo images.

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APPENDICES

Appendix A

Presentation and Proceeding paper: **Photometric Correction of Stereeographic Image Pairs**.

SUPPORTING DATA
See APPENDICES.

Photometric Correction of Stereographic Image Pairs

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Abstract

Differences in Photometric characteristics between images acquired during stereographic imaging may significantly reduce the effectiveness of their subsequent display or analysis. While uniform global differences can easily be corrected by applying traditional histogram matching techniques, these methods are not capable of dealing with differences that are object or distance dependent. We have developed a procedure to adjust locally, visual characteristics of one image in a stereo pair to match the alternate image. Objects, and their boundaries, are segmented in both images by detecting edges and depth discontinuities, and these features are used to partition the images into connected components. Where possible, stereo correspondences between components in each image are identified and used as the basis for local color correction. The fully automatic procedure is able to remove visible differences in most cases, but further development remains before the system will be sufficiently robust.

Introduction

Typically, stereographic image pairs are acquired on film or digitally, by methods such as synchronized exposures using multiple lenses and detectors; as a single exposure employing some form of beam splitter; or as a sequence of exposures by a single acquisition device which is moved appropriately between exposures. Whatever the acquisition paradigm, errors of either a geometric or photometric nature may occur. These errors can be a result of many factors such as different acquisition times, inadvertent camera motion between acquisitions, film-processing inconsistencies, differences between digital detectors, differences between lenses, and inaccuracies in the relative orientations of lenses. For stereopsis to be easily achieved when viewing stereoscopic image pairs, the geometric relationships between corresponding points must conform to the requirements of epipolar geometry and other visual differences must generally be small.

This manuscript is primarily concerned with correcting for inconsistencies in the photometric characteristics between images. More specifically, it is stipulated herein that for a given stereo image pair, their geometry is correct and one image is considered to be photometrically correct, while the alternate image is inconsistent with the first.

Prior attempts to adjust images in a pair of stereo exposures have generally relied on global methods such as various forms of white balancing or histogram equalization. These methods can be automated in a manner that provides reliable results in most cases, and are used routinely within our laboratory for postprocessing stereo image pairs. While these methods are able to correct for many types of systematic color shifts, they are inadequate for cases where differences are depth dependent or where surface reflectivity is such that an object's appearance changes rapidly or discontinuously with changing angle of view.

To improve our automated postprocessing procedures, we have been investigating object-based methods that attempt to identify corresponding foreground objects and adjust their photometric characteristics if there are significant disparities. This task is closely related to the problem of determining depth from stereo correspondence, as both involve matching objects between images in a stereo pair - which has proven to be very difficult. In fact, these tasks do not have a theoretical solution in general because it is possible to contrive stereo image pairs having no corresponding regions. In general, stereo image pairs will have some regions which correspond and some that do not, and in this situation there may be considerable ambiguity in how regions are to be identified together. Note that this ambiguity occurs both in computerized analysis as well as when a scene is being viewed by human observers, and is the source of many psychophysical depth illusions. The ultimate goal of this project is to use the information in a stereo pair to adjust the images to make it easier for viewers to achieve stereopsis.

Color Space Disclaimer

Within this manuscript we have deemphasized issues related to the exact color space under consideration and whether the color space has a true metric in the mathematical sense. While this allows us to sidestep many difficult technicalities, the main reason this is desirable is that many of our images are acquired with radiation sources other than light (e.g., x-rays) and assignment of a pseudocoloring is somewhat arbitrary. When these images are displayed they are subject to the constraints of color spaces and perceptual metrics, but the algorithms developed herein are applied to the originally acquired data and issues related to color spaces are not relevant at that point.

Methods

For the purposes of this manuscript, it is assumed that in the image pairs being processed the image planes are coplanar and that scan lines in each image are parallel to their common baseline. These conditions are sometimes specified by saying that the images have been rectified [1]. We also assume that the images were acquired or artificially generated at projection angles that are reasonably representative of human vision, and that the images are of normal kinds of scenes that have not been specifically contrived to defeat computer algorithms.

Object Segmentation

Each image in a pair is first segmented into coherent regions over which chromanence and brightness vary continuously. The process begins by identifying boundaries with an edge detector based on Cranny's algorithm [2]. Images are then partitioned into connected components over which the continuity constraints are enforced. An attempt is then made to establish stereo correspondence between images by independently matching epipolar pairs of scanlines to derive disparity and occlusion information. Our goal is to identify discontinuities in depth which indicate boundaries of objects. These methods have been proposed in computer vision literature by many [3-5] but the specific algorithm we employ, which was first proposed by Birchfield and Tomasi [6], is cvFindStereoCorrespondence(),contained in the openCV library. In this process, because we are primarily interested in larger forground regions, non-uniform regions and very small objects are either suppressed or combined into larger regions, while larger objects are retained. Not all regions can be unambiguously matched between images by this process. Unless the stereo correspondence can be determined with a high degree of confidence, the program does not attempt to correct the region. For each pair of corresponding connected components, a linear correction function that minimizes the sum-of-squares difference is determined.

We have developed software to implement these methods. The algorithms have a number of thresholds and parameters that need to be specified but otherwise operate automatically.

Luminance-Based Figures-of-Merit of Stereo Correspondence

As part of this work we have been investigating measures that are related to the amount of stereoscopic information contained within stereo image pairs. For a given pair of images, the central question is how closely one can come to generating the images in some sense, from projections of a geometrically viable 3D scene. In general, for scenes consisting of opaque surfaces, this does not have an analytical solution, and the effort required to solve it computationally is prohibitive. Thus, an optimal solution is not known and it is unlikely that there is a single measure that captures all aspects of stereo correspondence. Nevertheless we have devised two luminance-based figures-of-merit to measure different aspects of stereo correspondence. Both of these are most useful for evaluating small changes in images that are known to be related by stereo projection, and both behave somewhat unpredictably for large changes or for random images.

The first method produces a 2D scatter plot of luminance values from corresponding pixel pairs taken from the two views. The scatter plot is then analyzed for its degree of clustering, central tendency, and for certain aspects of its symmetry. This method does not require normalization but can be defeated when it is applied to image pairs that are not related by stereo projection. An example of a scatter plot generated by the method is shown in figure 1. This particular plot was generated for the left-eye and corrected right-eye images in figure 3. Note that the strong preponderance of points along the diagonal indicates that the images are very similar, while the deviation from linearity of the distribution is attributed to stereo disparity.

The second method begins by identifying the closest object appearing in both views. The two images are then aligned horizontally so that this object is in registration between the images and only the overlapping parts of the images are considered further. For each scan line in each image, pixel values are integrated along the scan line, and the resulting function is normalized so as to have a maximum value of one. The root-mean-square difference between each pair of corresponding scan lines is calculated and summed over all such pairs. For stereo pairs this gives a small value, and for random pairs a high value.

Test Image Pairs

As part of the development process, a number of synthetic pairs of images were generated, having known spatial relationships and photometric differences. These were intended to be of a very simple design, but they allowed the various algorithms to be tested. One such example is shown in figure 2 and discussed in the results below.

We also tested the procedures described above on a number of test image pairs that had been acquired with a pair of consumer digital cameras that had shutters wired together so that they would perform synchronously. In each case, one image in the pair showed both global and local differences relative to its reference image. These differences either occurred spontaneously because of inconsistencies in the cameras' automatic exposure calculation; by differences in the relative positioning of bright and dark objects relative to the cameras' sensors; by placing neutral density filters over one camera only; or more likely, by the authors intentionally misadjusting white balance and speed settings. An example of one of these pairs is shown in figure 3.

In our laboratory we are mainly interested in the application of stereographic methods to radiographic images. This is becoming increasingly important as Radiology moves toward the digital acquisition of large 3D datasets. Figure 4 presents a stereo pair of x-ray projections of a breast that were acquired with a breast tomosynthesis system. A single breast exam may acquire many such pairs and these kinds of procedures necessitate automated image correction.

All stereo pairs were processed with the above algorithms and a figure-of-merit was calculated before and after the correction.

Results

Figure 2a and 2b represent right- and left-eye projections of a 3D space consisting of a square, circle and triangle at varying distances from the observer. Colors of the image in 2b were intentionally changed to test our algorithm's ability to make a suitable correction. Note that colors in each object were altered separately so there is no global adjustment that can adequately reduce the differences. Figures 2c and 2d show the result of the segmentation and depth evaluation, and our use of gray values to label the depth of each object. The corrected version of 2b is shown in 2f.

Figure 3a and 3b are the left- and right-eye views of a stereo pair, where 2b exhibits an overall blue cast, and the small yellow boat on the right appears to have been incorrectly recorded. Manually removing the blue cast did not greatly improve the hue of the small boat. However, the algorithm was able to perform both a global color correction and locally improve the boat's color.

In each of these cases, the algorithm was able to decrease color discrepancies between the images, though the corrections were less than what could have been achieved with a manual procedure.

Figure 4a was considered to be a correct left-projection and 4b was the corresponding right-projection. Figure 4e is the corrected version of 4b. Figures 4c and 4f are the scatter plots associated with the uncorrected and corrected images, respectively.

Discussion and Conclusions

At this stage of development, it is not possible to implement the kinds of corrections considered herein in a fully automatic procedure. This is largely due to the inherent ambiguities in identifying corresponding regions between images – a task that is not always solvable by either computers or humans, but is much more difficult for computers. Also, because 3D shape information is reflected in subtle photometric differences in views at slightly different viewing angles, there is a limit as to how much correction is actually desirable. Issues of this type must rest on the expertise of human observers, until a more comprehensive theory of stereo vision provides guidance. But in the end, if photometric information about a scene has been degraded in one image of a stereo pair, there will not be enough information to correct unambiguously the image.

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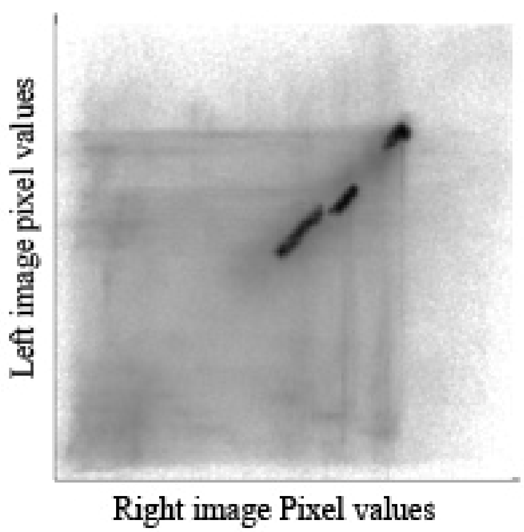

Figure1. Scatter point derived in figure-of-merit calculation for left-eye and corrected right-eye images in figure 3.

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Author Biography

Xiao Hui Wang received her M.D. from Shanghai Second Medical College in 1982. In 1994, she received her Ph.D. in neuroscience from Medical College of Pennsylvania, and in 2001, she received her MS degree in Information Sciences from the University of Pittsburgh. She is a Research Assistant Professor with the Department of Radiology at the University of Pittsburgh. Her research interests include medical image processing, visualization, and computer-assisted detection on medical images.

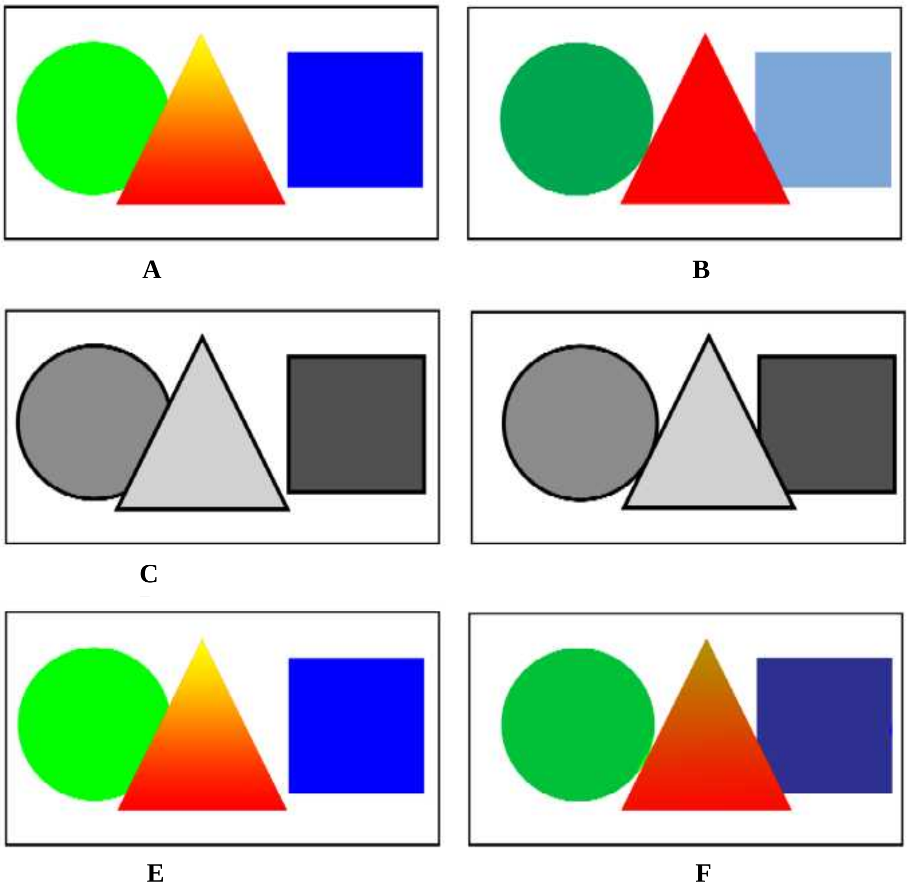

Figure2. A synthetically generated stereo pair of three geometric forms at varying distances from the observer. A and B are the original right- and left-eye images respectively. C and D show how the regions were segmented and labeled with distance (i.e., shade of gray).

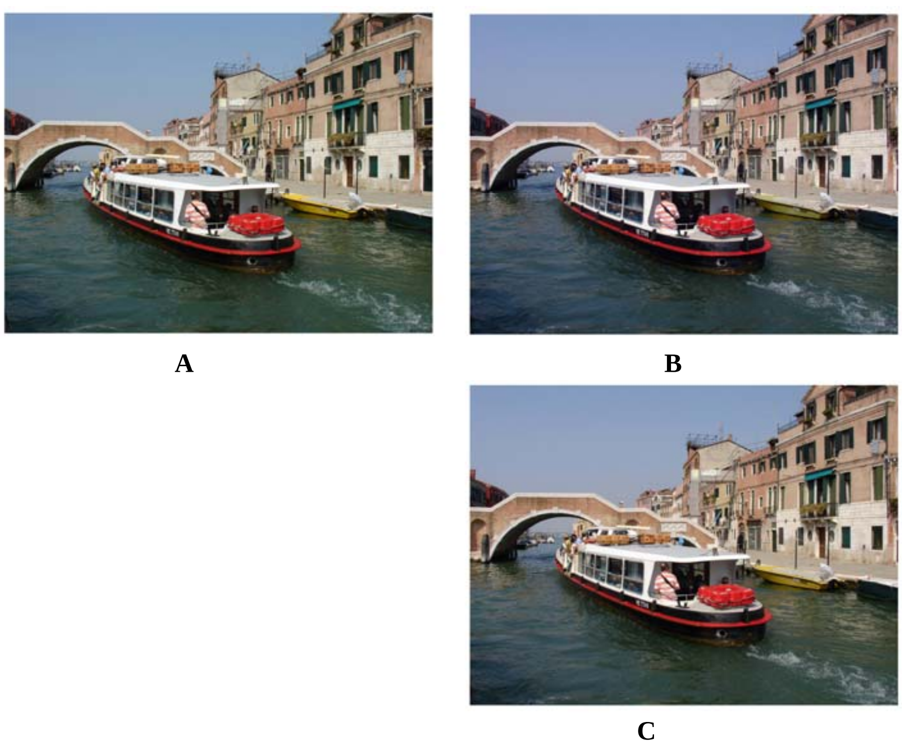

Figure3. A and B represent the left-eye and right-eye images in a stereo pair. Image C is the result of correcting B to match A.

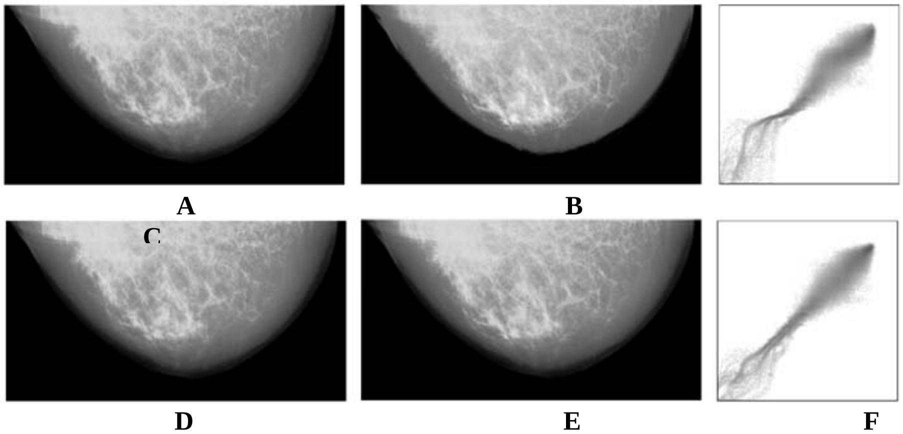

Figure4. A and B are a left- and right-view of breast projections acquired by X-ray tomography. E is the result of correcting B to match A. C and F are the scatter plots generated by the uncorrected and corrected pairs respectively.